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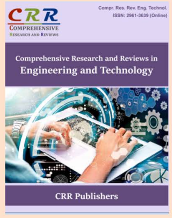

(REVIEW ARTICLE)

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Eco-friendly wastewater treatment technologies (concept): Conceptualizing advanced, sustainable wastewater treatment designs for industrial and municipal applications

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Abstract

This concept paper explores the development and integration of advanced, sustainable wastewater treatment technologies designed for both industrial and municipal applications. As environmental concerns rise globally, the need for eco-friendly solutions in water management has become critical. The proposed approach focuses on enhancing wastewater treatment systems through innovative, sustainable designs that reduce environmental impact, optimize resource recovery, and promote energy efficiency. Key components of this concept include the utilization of natural treatment processes such as constructed wetlands, biofiltration, and phytoremediation, combined with cutting-edge technologies like membrane bioreactors, anaerobic digestion, and advanced oxidation processes. These methods aim to minimize the reliance on chemical treatments, reduce greenhouse gas emissions, and ensure high levels of water quality for reuse or safe discharge. The design framework prioritizes energy-efficient operations, leveraging renewable energy sources such as solar and wind power to drive treatment facilities. Additionally, resource recovery techniques are integrated, allowing for the capture of nutrients and energy from wastewater, supporting the circular economy and contributing to sustainability goals. The concept is adaptable to a range of industrial and municipal needs, offering scalable solutions that can address small, decentralized systems or large, urban treatment plants. The implementation of smart sensors and data analytics further enhances operational efficiency, ensuring real-time monitoring and optimization of treatment processes. By integrating eco-friendly wastewater treatment technologies, this concept aims to provide a holistic, sustainable solution to managing wastewater, improving water quality, and minimizing the ecological footprint of treatment facilities. The approach supports both environmental preservation and regulatory compliance, offering a pathway to more resilient and sustainable water management systems globally.

Keywords: Eco-friendly wastewater treatment; Energy efficiency; Municipal applications

1 Introduction

The increasing demand for sustainable water management in the face of growing environmental challenges has driven the need for innovative wastewater treatment solutions. Industrial and municipal sectors, being significant contributors to water pollution, must adopt advanced technologies that not only treat wastewater effectively but also minimize ecological footprints (Afeku-Amenyo, 2024, Emeihe, et al., 2024, Ige, Kupa & Ilori, 2024). Conventional wastewater

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treatment methods, while effective in removing contaminants, often rely on energy-intensive processes and chemicals, leading to high operational costs and environmental degradation (Anyanwu, et al., 2024, Kupa, et al., 2024, Nwaimo, Adegbola & Adegbola, 2024).

This concept paper introduces eco-friendly wastewater treatment technologies, aimed at conceptualizing advanced, sustainable designs that address both the environmental and operational challenges of wastewater treatment (Tomassoni, et al., 2013, Tuboalabo, et al., 2024). The focus is on integrating natural processes with state-of-the-art technological advancements to create treatment systems that are efficient, scalable, and adaptable to diverse industrial and municipal applications (Enahoro, et al., 2024, Olanrewaju, Daramola & Babayeju, 2024). These systems prioritize reducing energy consumption, maximizing resource recovery, and promoting water reuse, all while ensuring compliance with increasingly stringent environmental regulations.

The development of such technologies involves incorporating renewable energy sources, advanced filtration techniques, and biological treatment methods to create a closed-loop system that not only treats wastewater but also recovers valuable resources such as energy, water, and nutrients (Ajiga, et al., 2024, Ezeafulukwe, et al., 2024, Nasuti, et al., 2008, Nwaimo, Adegbola & Adegbola, 2024). By aligning with circular economy principles, eco-friendly wastewater treatment technologies aim to transform wastewater from a liability into a resource, contributing to a more sustainable and resilient water management framework for future generations.

This paper will explore various sustainable wastewater treatment methods, assess their potential applications, and outline the benefits of adopting eco-friendly designs for both industrial and municipal wastewater treatment systems.

Water is an essential resource for both industrial processes and human consumption, yet the management of wastewater remains a global environmental challenge. The discharge of untreated or inadequately treated wastewater from industrial and municipal sources has contributed significantly to water pollution, threatening ecosystems, public health, and biodiversity (Ajiga, et al., 2024, Chinyere, Anyanwu & Innocent, 2023, Daramola, 2024). Traditional wastewater treatment systems, while effective in removing pollutants, often rely on energy-intensive processes, chemical additives, and extensive infrastructure, which can have adverse environmental impacts and contribute to climate change (Ige, Kupa & Ilori, 2024, Ijomah, et al., 2024, Moones, et al., 2023). In recent years, the push for sustainability has highlighted the need for eco-friendly wastewater treatment solutions that reduce energy consumption, minimize chemical usage, and promote resource recovery. Innovations in green technologies and the adoption of circular economy principles have opened new avenues for designing wastewater treatment systems that not only meet regulatory requirements but also enhance environmental stewardship (Arowoogun, et al., 2024, Ezeafulukwe, et al., 2024, Kupa, et al., 2024).

The global water crisis and growing environmental regulations have put pressure on industries and municipalities to adopt more sustainable practices. In response, advanced wastewater treatment technologies that integrate natural processes, energy-efficient designs, and resource recovery techniques are emerging as viable alternatives to conventional methods (Ajiga, et al., 2024, Ilori, Nwosu & Naiho, 2024, Nwaimo, Adegbola & Adegbola, 2024). These eco-friendly technologies focus on using renewable energy sources, biological processes, and smart monitoring systems to achieve high treatment efficiency with a reduced carbon footprint. For industrial applications, particularly in sectors such as manufacturing, mining, and energy, sustainable wastewater treatment is crucial for reducing operational costs, enhancing water reuse, and ensuring regulatory compliance (Afeku-Amenyo, 2024, Daramola, et al., 2024, Nwosu, 2024, Olanrewaju, Daramola & Ekechukwu, 2024). Municipal wastewater systems, serving urban and rural populations, are also under increasing pressure to adopt technologies that support water conservation and reduce the environmental impacts of wastewater discharge.

This background provides a foundation for exploring advanced wastewater treatment designs that align with sustainability goals, offering solutions for both industrial and municipal sectors. By conceptualizing eco-friendly technologies, this approach seeks to promote water reuse, energy efficiency, and resource recovery, contributing to a more resilient and sustainable future for water management systems worldwide (Ajiga, et al., 2024, Ezeafulukwe, et al., 2024, Nwaimo, Adegbola & Adegbola, 2024).

1.1.1 Key Dataset

To conceptualize and design advanced, sustainable wastewater treatment technologies for industrial and municipal applications, a robust and diverse set of data is critical. The key dataset should encompass various environmental, operational, and technological parameters that influence the design, implementation, and effectiveness of eco-friendly wastewater treatment systems (Daramola, et al., 2024, Ezeh, Ogbu & Heavens, 2023, Nwaimo, et al., 2024). Water quality data is essential, including the characteristics of influent and effluent such as contaminants like biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), nitrogen, phosphorus, heavy metals, pathogens, and emerging pollutants like pharmaceuticals and microplastics. Additional factors such as pH, temperature, conductivity, toxicity levels, and microbial content also play a crucial role in determining the appropriate treatment technologies and processes (Ezeh, et al., 2024, Ilori, Nwosu & Naiho, 2024, Omaghomi, et al., 2024). Flow rate data, including daily and peak flow rates, provides insight into the volume of wastewater generated, which is critical for designing systems with the proper capacity and scalability. It is also important to account for seasonal and operational fluctuations in wastewater flow, as these variations impact the adaptability of the treatment technology.

Energy consumption data helps establish the energy requirements of conventional treatment methods such as aeration, pumping, and chemical treatments. This provides a baseline for measuring improvements in energy efficiency with eco-friendly alternatives. Data on the potential for renewable energy sources, such as solar, wind, or biogas, is also necessary to explore energy-efficient designs (Ajiga, et al., 2024, Nwaimo, et al., 2024, Onyekwelu, et al., 2024). Comparative metrics on the energy efficiency of advanced technologies like membrane bioreactors, anaerobic digestion, or advanced oxidation processes are essential for evaluating sustainability. Resource recovery potential is a key consideration. Data on nutrient content, including nitrogen and phosphorus, is useful for determining resource recovery options, such as for agricultural applications. Similarly, information on the quantity of organic matter in wastewater can inform biogas production through anaerobic digestion (Akinsulire, et al., 2024, Ezeh, et al., 2024, Omaghomi, et al., 2024). Data on the required quality standards for water reuse, whether for irrigation, industrial cooling, or potable reuse, is also critical for treatment design.

Environmental impact data, such as greenhouse gas emissions from traditional treatment processes like methane and CO2, helps assess the potential for emissions reduction using eco-friendly technologies. Information on the health and vulnerability of ecosystems receiving treated wastewater is vital for determining the level of treatment needed (Ilori, Nwosu & Naiho, 2024, Nwosu & Ilori, 2024, Ozowe, et al., 2024). Additionally, biodiversity impact data is necessary to understand how wastewater discharge affects local flora and fauna, particularly in nature-based treatment solutions. Regulatory compliance data is essential, covering local, national, and international water quality standards that must be met for effluent discharge and water reuse (Daramola, et al., 2024, Ozowe, Daramola & Ekemezie, 2023, Tomassoni, et al., 2012). This includes parameters such as pollutant limits and acceptable treatment methods. Sector-specific regulations, for industries like mining, oil and gas, or food processing, must also be considered when selecting technologies (Nwankwo, 2013, Ozowe, Daramola & Ekemezie, 2024).

Cost data, including capital and operational expenses for various treatment technologies, provides a comparative understanding of the financial investment required. It is important to assess potential cost savings from resource recovery, such as revenue generated from recovered water, energy, or nutrients (Akinsulire, et al., 2024, Tomassoni, et al., 2013). Technology performance data is crucial for understanding the treatment efficiency of eco-friendly methods, including biological, chemical, and physical processes. Lifecycle analysis data is needed to evaluate the long-term performance and environmental impact of different technologies. Data from pilot projects and real-world applications of eco-friendly wastewater treatment in industrial and municipal settings offers valuable insights into scalability and adaptability (Nwosu, Babatunde & Ijomah, 2024, Obijuru, et al., 2024).

Geographic and climate data, including weather patterns, climate conditions, and geographic characteristics such as soil types and groundwater levels, inform site-specific design considerations, especially for decentralized or nature-based systems like constructed wetlands or solar-powered solutions (Ezeh, et al., 2024, Ilori, Nwosu & Naiho, 2024, Porlles, et al., 2023). Public and community data, including public perception and acceptance of wastewater reuse, decentralized systems, and the use of treated water for potable or non-potable purposes, is vital for the success of these technologies. Insights from stakeholders, including industry representatives, government officials, and local communities, on the adoption of sustainable wastewater treatment technologies are also important for aligning with regulatory frameworks and long-term environmental goals (Nwankwo, et al., 2024, Odilibe, et al., 2024, Soyombo, et al., 2024).

By collecting and analyzing this key dataset, it becomes possible to design and implement eco-friendly wastewater treatment technologies that are efficient, cost-effective, scalable, and environmentally sustainable, addressing both industrial and municipal needs while promoting water conservation and resource recovery (Akinsulire, et al., 2024, Daramola, et al., 2024, Ozowe, Daramola & Ekemezie, 2023).

1.2 Overview

The increasing environmental concerns and the need for sustainable water management have driven significant innovation in wastewater treatment technologies for industrial and municipal applications. Traditional wastewater treatment methods, while effective in removing contaminants, often involve energy-intensive processes, reliance on chemical additives, and high operational costs (Datta, et al., 2023, Nwankwo, et al., 2023). These approaches, though widespread, do not align with contemporary goals of reducing ecological footprints and conserving resources. As global water demands increase and environmental regulations become stricter, the need for advanced, eco-friendly wastewater treatment systems has become more urgent (Ezeh, et al., 2024, Odonkor, Eziamaka & Akinsulire, 2024).

Eco-friendly wastewater treatment technologies offer sustainable alternatives to conventional systems by integrating natural processes, renewable energy sources, and resource recovery techniques. These advanced designs aim to treat wastewater efficiently while minimizing energy consumption, reducing chemical usage, and enabling the reuse of treated water (Dozie, et al., 2024, Ilori, Nwosu & Naiho, 2024). A core principle of these systems is the application of circular economy concepts—treating wastewater not as waste but as a resource that can be recycled for energy production, nutrient recovery, and water reuse.

In industrial applications, these technologies provide solutions for sectors such as manufacturing, mining, and energy, where wastewater is often laden with complex pollutants. For municipal systems, they offer scalable designs to handle varying volumes and qualities of wastewater while promoting water conservation and public health (Akinsulire, et al., 2024, Ebeh, et al., 2024, Iwuanyanwu, et al., 2024). By adopting innovative biological, physical, and chemical treatment processes, these systems seek to reduce the environmental impact of wastewater discharge and contribute to long-term water sustainability. Eco-friendly wastewater treatment technologies combine innovations like anaerobic digestion, membrane bioreactors, constructed wetlands, and advanced oxidation processes (Eziamaka, Odonkor & Akinsulire, 2024). These solutions are often powered by renewable energy, such as solar or wind, further enhancing their sustainability profile. Moreover, these systems are designed to be adaptable to local geographic, climatic, and regulatory conditions, making them suitable for diverse industrial and municipal applications globally (Nwankwo, et al., 2024, Odonkor, Eziamaka & Akinsulire, 2024).

This concept explores the potential of these advanced wastewater treatment designs, highlighting their benefits for environmental conservation, regulatory compliance, and economic feasibility. By focusing on efficiency, resource recovery, and adaptability, eco-friendly wastewater treatment technologies represent a forward-thinking approach to addressing one of the most pressing environmental challenges of our time (Akinsulire, et al., 2024, Ogbonna, et al., 2012, Tuboalabo, et al., 2024).

1.3 Literature Review

The development of eco-friendly wastewater treatment technologies has been driven by growing environmental concerns, regulatory pressures, and the need for resource efficiency. Existing literature extensively covers the evolution of these technologies, emphasizing advancements in biological, physical, and chemical processes aimed at enhancing sustainability in both industrial and municipal contexts (Ebeh, et al., 2024, Eziamaka, Odonkor & Akinsulire, 2024).

Traditional wastewater treatment systems have typically involved three stages: primary (physical removal of solids), secondary (biological treatment to degrade organic matter), and tertiary treatment (advanced processes to remove remaining pollutants). These systems, while effective, are energy-intensive, consume significant chemicals, and often result in by-products, such as sludge, that require further processing (Iwuanyanwu, et al., 2022, Nwankwo, et al., 2023). Literature on conventional systems highlights their limitations in meeting modern sustainability goals, particularly in regions facing water scarcity, high energy costs, and stringent regulations (Adebimpe, Kupa & Ilori, 2024, Metcalf & Eddy, 2014). Recent studies indicate that eco-friendly wastewater technologies are emerging as a sustainable alternative to conventional treatment systems. These technologies integrate renewable energy sources, resource recovery, and low-energy treatment processes to minimize environmental impacts while enhancing efficiency (Afeku-Amenyo, 2021, Kehrein et al., 2020, Ogbonna, Oparaocha & Anyanwu, 2024). The literature stresses the need for more sustainable approaches as population growth and industrialization escalate water demands and pollution levels.

Biological treatment processes, particularly anaerobic digestion, have gained prominence in eco-friendly wastewater management. Anaerobic digestion offers the dual benefits of treating wastewater and generating biogas, which can be used as a renewable energy source. Several studies highlight the effectiveness of anaerobic reactors in reducing organic pollutants and producing methane, reducing the carbon footprint of wastewater treatment (Akinsulire, et al., 2024, Ebeh, et al., 2024, Wang et al., 2019). Membrane bioreactors (MBRs), which combine biological treatment with membrane filtration, have also been extensively studied for their high removal efficiency of organic pollutants and pathogens while requiring less physical space than traditional systems (Afeku-Amenyo, 2015, Akomolafe, et al., 2024, Judd, 2017).

Constructed wetlands, another biological treatment option, are widely studied for their ability to mimic natural processes. These systems use plant species, soil, and microbial communities to filter and break down contaminants. Literature on constructed wetlands emphasizes their low-energy consumption, ability to handle variable flow rates, and the added benefit of enhancing local biodiversity (Adebimpe, Kupa & Ilori, 2024, Tomassoni, et al., 2013, Vymazal, 2018). However, research also highlights their limitations in treating industrial wastewater with heavy metals or toxic chemicals, suggesting that they are more effective for municipal applications (Kadlec & Wallace, 2009, Tuboalabo, et al., 2024).

Advanced oxidation processes (AOPs) represent a chemical approach to eco-friendly wastewater treatment, particularly effective in removing emerging contaminants such as pharmaceuticals and endocrine disruptors. AOPs involve generating highly reactive hydroxyl radicals that break down complex organic molecules into simpler, non-toxic compounds (Eziamaka, Odonkor & Akinsulire, 2024). Studies demonstrate the potential of AOPs in achieving high pollutant removal rates while minimizing by-products, making them a promising solution for both industrial and municipal wastewater (Alemede, et al., 2024, Ebeh, et al., 2024, Oturan & Aaron, 2014). However, the high energy consumption of AOPs remains a significant barrier to widespread adoption, particularly in low-resource settings.

Literature increasingly emphasizes the integration of circular economy principles into wastewater treatment, where wastewater is seen not as waste but as a resource. Nutrient recovery, particularly nitrogen and phosphorus, is a central theme in this domain. Technologies such as struvite precipitation allow for the recovery of phosphorus from wastewater, which can then be reused as fertilizer in agriculture (Batstone et al., 2015, Iwuanyanwu, et al., 2024). Studies highlight the environmental and economic benefits of nutrient recovery, particularly in reducing the reliance on synthetic fertilizers, which are energy-intensive to produce (Cornel & Schaum, 2009, Ogbonna, et al., 2024).

Water reuse is another critical focus in eco-friendly wastewater literature. Reclaimed water from treatment processes can be repurposed for agricultural irrigation, industrial cooling, or even potable use in regions facing water scarcity. Numerous studies highlight successful case studies of wastewater reuse in agriculture, reducing freshwater demand and enhancing sustainability in arid regions (Afeku-Amenyo, 2022, Angelakis et al., 2018, Iwuanyanwu, et al., 2024). However, concerns remain about the long-term impacts of micropollutants in reclaimed water, suggesting the need for more research on treatment technologies that can fully remove these contaminants.

The literature also explores ways to reduce the energy footprint of wastewater treatment systems through the integration of renewable energy sources. Studies show that coupling wastewater treatment with renewable energy, such as solar or wind, can significantly reduce operational costs and carbon emissions (Eziamaka, Odonkor & Akinsulire, 2024, Gabrielli, et al., 2010). For example, solar-powered treatment systems have shown promise in off-grid applications, particularly in remote or rural areas with limited access to electricity (Alemede, et al., 2024, Lefebvre et al., 2020). Incorporating energy-efficient technologies like anaerobic digestion, which produces biogas from organic waste, is another key area of research. Studies demonstrate that wastewater treatment plants can achieve energy neutrality or even generate surplus energy by recovering biogas for use in electricity generation or heating (Ebeh, et al., 2024, Gil-Ozoudeh, et al., 2024, Zitomer & Himmelblau, 2020). This integration of energy recovery into wastewater treatment aligns with broader sustainability goals and contributes to the circular economy.

Despite the potential benefits, the adoption of eco-friendly wastewater treatment technologies faces several challenges. High capital costs, technological complexity, and the need for skilled labor to operate advanced systems are recurring themes in the literature (Gude, 2015, Iwuanyanwu, et al., 2024, Nwankwo, Tomassoni & Tayebati, 2012, Toromade, et a., 2024). There are also regulatory hurdles, as many jurisdictions have stringent water quality standards that eco-friendly technologies must meet. While decentralized systems like constructed wetlands are often praised for their low energy consumption and minimal maintenance, they may not be suitable for large-scale industrial applications due to limited capacity and potential space constraints (Afeku-Amenyo, 2024, Stefanakis et al., 2014, Ogedengbe, et al., 2024).

The literature suggests that for widespread adoption, further research and development are needed to enhance the efficiency, cost-effectiveness, and scalability of these technologies. Studies emphasize the importance of pilot projects and case studies to demonstrate the viability of eco-friendly wastewater solutions in diverse industrial and municipal contexts (Gil-Ozoudeh, et al., 2023, Verlicchi & Zambello, 2016, Ogugua, et al., 2024).

In summary, the literature on eco-friendly wastewater treatment technologies reveals a growing emphasis on sustainable, energy-efficient, and resource-recovery-focused approaches. While biological methods like anaerobic digestion and constructed wetlands, as well as chemical processes like AOPs, show significant promise, challenges related to cost, energy use, and scalability remain (Alemede, et al., 2024, Ebeh, et al., 2024, Jambol, et al., 2024). The ongoing research into integrating renewable energy sources and circular economy principles into wastewater treatment offers a promising path forward for creating more sustainable industrial and municipal water management systems. However, further innovation and investment are required to overcome the barriers to widespread adoption and to meet the evolving regulatory and environmental demands (Tayebati, et al., 2010, Tomassoni, et al., 2013, Toromade, et a., 2024).

1.4 Research Gap

While significant progress has been made in developing eco-friendly wastewater treatment technologies, there remain critical gaps that hinder the full realization of sustainable solutions for both industrial and municipal applications. A major research gap lies in the scalability of many advanced eco-friendly wastewater technologies (Anyanwu & Ogbonna, 2023, Ekechukwu, Daramola & Kehinde, 2024). Although processes like anaerobic digestion, membrane bioreactors, and constructed wetlands show promise at pilot scales, their implementation on a large, industrial scale presents significant challenges (Afeku-Amenyo, 2024, Gil-Ozoudeh, et al., 2022, Ogugua, et al., 2024). There is limited data on the long-term cost-effectiveness of these systems in real-world applications, especially when considering the high capital costs of advanced technologies. More research is needed to optimize these systems for larger-scale operations without compromising sustainability.

Advanced oxidation processes (AOPs) are highly effective in removing emerging contaminants such as pharmaceuticals and micropollutants. However, they remain energy-intensive, and the literature lacks comprehensive solutions for reducing energy consumption in these systems (Gil-Ozoudeh, et al., 2022, Khosrow Tayebati, Nwankwo & Amenta, 2013). Research is needed to develop lower-energy alternatives or to improve the energy efficiency of existing AOPs to make them viable in resource-limited settings. While nutrient and energy recovery from wastewater is a growing area of interest, current technologies still face limitations in terms of efficiency and recovery rates (Tayebati, et al., 2011, Tomassoni, et al., 2013, Toromade, et a., 2024). The integration of resource recovery into wastewater treatment processes is underexplored, particularly in regions where water reuse and nutrient recovery could provide substantial economic benefits. There is a need for further research into optimizing recovery processes, particularly in nutrient-deficient regions where phosphorus and nitrogen recovery could alleviate dependence on synthetic fertilizers (Nwankwo, et al., 2011, Ogugua, et al., 2024).

Although some technologies show promise in removing traditional contaminants from wastewater, emerging pollutants such as microplastics, nanomaterials, and endocrine disruptors remain inadequately addressed (Ekechukwu, Daramola & Olanrewaju, 2024, Ogunbiyi, et al., 2024). More studies are needed to assess the efficacy of eco-friendly wastewater treatment technologies in removing these complex and persistent pollutants, which pose significant risks to environmental and human health. While the integration of renewable energy sources into wastewater treatment has shown potential for reducing the environmental impact of these systems, there is a lack of comprehensive research on how to best integrate technologies like solar, wind, and biogas recovery into treatment plants (Okatta, Ajayi & Olawale, 2024, Tomassoni, et al., 2013, Toromade, et a., 2024). Further studies are needed to explore hybrid renewable energy systems that can efficiently power wastewater treatment processes, particularly in off-grid or remote areas.

Constructed wetlands and other low-energy, decentralized systems have been well-studied in the context of municipal wastewater treatment, but their application in industrial settings remains underexplored. More research is required to adapt these technologies for industrial wastewater, which often contains higher levels of pollutants and toxic chemicals that challenge traditional eco-friendly approaches (Afeku-Amenyo, 2024, Emeihe, et al., 2021). Regulatory frameworks for eco-friendly wastewater treatment technologies are still developing, and there is a research gap in understanding how policy can support the adoption and standardization of these technologies. More research is needed to align technological innovations with regulatory standards and to explore incentives that could encourage industries and municipalities to adopt sustainable wastewater treatment methods (Gil-Ozoudeh, et al., 2024, Khosrow Tayebati, et al., 2013, Tuboalabo, et al., 2024).

Addressing these research gaps is essential for advancing eco-friendly wastewater treatment technologies and ensuring their broad, sustainable implementation in both industrial and municipal contexts. Further interdisciplinary collaboration among engineers, environmental scientists, and policymakers is needed to bridge these gaps and foster innovation in the field (Anyanwu, et al., 2024, Kuo, et al., 2019, Kupa, et al., 2024, Okatta, Ajayi & Olawale, 2024).

1.5 Problem Statement

The increasing demand for clean water, coupled with the escalating environmental concerns surrounding conventional wastewater treatment processes, has highlighted the urgent need for sustainable and eco-friendly wastewater treatment technologies. Current treatment methods, while effective in pollutant removal, often rely on energy-intensive processes, generate secondary pollutants, or fail to adequately address emerging contaminants like microplastics, pharmaceuticals, and endocrine disruptors. Moreover, traditional wastewater treatment plants contribute significantly to greenhouse gas emissions, and many do not incorporate resource recovery practices, such as nutrient or energy extraction. Municipalities and industries face significant challenges in scaling advanced, environmentally sustainable wastewater technologies to meet growing regulatory pressures and environmental goals. Additionally, there is a gap in integrating renewable energy sources into treatment systems, which could reduce the carbon footprint of wastewater facilities. Despite the development of promising innovations such as membrane bioreactors, constructed wetlands, and anaerobic digestion, their scalability, cost-effectiveness, and adaptability for different wastewater streams remain barriers to widespread adoption. Thus, the central problem is how to conceptualize and design advanced wastewater treatment technologies that are not only capable of treating a wide range of contaminants but are also energy-efficient, cost-effective, and scalable for both industrial and municipal applications, while promoting circular economy principles through resource recovery and minimizing environmental impact. Addressing this problem is crucial to ensuring sustainable water management practices in a world facing increasing water scarcity and environmental degradation.

1.6 Objectives

The primary objective of this research is to conceptualize and develop advanced, eco-friendly wastewater treatment technologies that effectively address the challenges faced by both industrial and municipal applications. This objective encompasses several key aims:

- Innovate Sustainable Treatment Designs: To design and propose innovative wastewater treatment systems that integrate biological, physical, and chemical processes to enhance pollutant removal efficiency while minimizing energy consumption and environmental impact.
- Promote Resource Recovery: To explore and incorporate methods for resource recovery, including nutrient extraction and energy generation, into wastewater treatment processes, thereby supporting circular economy principles and reducing reliance on synthetic inputs.
- Evaluate Emerging Contaminant Removal: To assess the efficacy of proposed treatment technologies in removing emerging contaminants, such as pharmaceuticals and microplastics, ensuring that the solutions meet current and future regulatory standards.
- Assess Scalability and Cost-Effectiveness: To evaluate the scalability and economic viability of the developed technologies, identifying barriers and potential solutions for implementation in diverse settings, including small-scale and resource-limited environments.
- Integrate Renewable Energy Sources: To investigate the integration of renewable energy solutions, such as solar and biogas, into wastewater treatment systems, aiming to enhance sustainability and reduce carbon emissions associated with conventional treatment methods.
- Foster Collaboration and Knowledge Sharing: To engage stakeholders from industry, academia, and government to promote knowledge sharing, pilot projects, and best practices that facilitate the adoption of eco-friendly wastewater treatment technologies.

By achieving these objectives, the research aims to contribute significantly to the advancement of sustainable wastewater management practices, ultimately improving water quality and environmental health.

1.7 Expected Outcomes

The expected outcomes of this research on eco-friendly wastewater treatment technologies are as follows:

- Innovative Treatment Designs: Development of advanced, sustainable wastewater treatment designs that effectively integrate multiple processes to enhance pollutant removal while reducing energy consumption and environmental impact.
- Resource Recovery Models: Creation of viable models for resource recovery that demonstrate the potential for extracting valuable nutrients and generating renewable energy from wastewater, supporting a circular economy.
- Enhanced Removal of Emerging Contaminants: Evidence-based evaluation of the proposed technologies' efficacy in removing emerging contaminants, ensuring compliance with current and anticipated regulatory standards for wastewater treatment.
- Scalability Framework: Identification of best practices and frameworks for scaling the proposed technologies, making them adaptable for diverse industrial and municipal contexts, including small-scale and resource-limited settings.
- Renewable Energy Integration: Guidelines for integrating renewable energy sources into wastewater treatment systems, demonstrating how these solutions can reduce the carbon footprint of treatment processes and promote sustainability.

- Stakeholder Engagement and Collaboration: Establishment of partnerships among stakeholders, including industries, municipalities, and research institutions, to facilitate the sharing of knowledge and resources, leading to pilot projects and successful implementation of eco-friendly technologies.
- Policy Recommendations: Formulation of policy recommendations to support the adoption and standardization of eco-friendly wastewater treatment practices, addressing regulatory barriers and promoting financial incentives for implementation.
- Contributions to Sustainable Water Management: A significant contribution to the field of sustainable water management, providing insights and practical solutions that enhance water quality, promote environmental health, and address the challenges of water scarcity and pollution.

By achieving these outcomes, the research aims to pave the way for more effective, sustainable wastewater treatment solutions that meet the needs of both industrial and municipal applications while safeguarding the environment.

1.8 Challenges and Barriers

The development and implementation of eco-friendly wastewater treatment technologies face several challenges and barriers that can hinder their effectiveness and widespread adoption: : Advanced treatment technologies often require significant upfront capital investment for infrastructure and equipment (Anyanwu, et al., 2024, Emeihe, et al., 2022, Kupa, et al., 2024). This financial barrier can deter municipalities and industries, particularly in resource-limited settings, from adopting innovative solutions. Many eco-friendly treatment processes, such as membrane bioreactors and anaerobic digestion, involve complex operations and require specialized knowledge for effective management and maintenance (Afeku-Amenyo, 2024, Gyimah, et al., 2023, Okatta, Ajayi & Olawale, 2024). This complexity can lead to operational challenges and may necessitate extensive training for personnel.

Existing regulatory frameworks may not adequately support the adoption of new technologies. Strict compliance requirements, lack of clear guidelines for innovative practices, and slow regulatory approval processes can pose significant barriers to implementation (Ige, Kupa & Ilori, 2024, Okeleke, et al., 2023). There may be a lack of awareness among stakeholders about the benefits and effectiveness of eco-friendly wastewater treatment technologies. Resistance to change and a preference for conventional methods can impede the acceptance and integration of new systems (Tayebati, et al., 2012, Tuboalabo, et al., 2024). Industrial and municipal wastewater streams can vary significantly in composition and concentration of pollutants, making it challenging to design universally applicable treatment solutions (Nwankwo, et al., 2012, Okeleke, et al., 2024, Olaleye, et al., 2024). Technologies that perform well under specific conditions may not be effective in diverse settings.

While resource recovery is a key goal, the actual extraction of nutrients and energy from wastewater can be technically challenging and economically unviable without appropriate technology and infrastructure. This can limit the effectiveness of treatment processes. Retrofitting existing wastewater treatment plants with new technologies can be logistically and financially challenging (Emeihe, et al., 2024, Kupa, et al., 2024, Olaniyi, et al., 2024). Integrating eco-friendly solutions into established infrastructure requires careful planning and investment. Some eco-friendly treatment technologies, despite their sustainability benefits, may still have high energy demands. Balancing energy consumption with treatment efficiency is crucial, particularly in regions with limited energy resources (Nwobodo, Nwaimo & Adegbola, 2024, Okoduwa, et al., 2024).

here is often insufficient data on the long-term performance and effectiveness of new eco-friendly technologies. This lack of empirical evidence can hinder decision-making and investment in innovative solutions (Anyanwu, et al., 2024, Olanrewaju, Daramola & Babayeju, 2024). Limited access to funding and financial support mechanisms can restrict the development and deployment of eco-friendly wastewater treatment technologies, particularly in developing regions where resources are scarce (Tayebati, et al., 2013). Addressing these challenges and barriers is essential for advancing the field of eco-friendly wastewater treatment technologies and ensuring their successful implementation in both industrial and municipal contexts. Collaborative efforts among researchers, policymakers, and industry stakeholders will be crucial in overcoming these obstacles (Ige, Kupa & Ilori, 2024, Nwobodo, Nwaimo & Adegbola, 2024).

2 Methodology

The methodology for conceptualizing advanced eco-friendly wastewater treatment technologies involves a systematic approach that integrates research, design, testing, and stakeholder engagement. The following steps outline this methodology:

- Literature Review

Conduct a comprehensive review of existing research on eco-friendly wastewater treatment technologies, focusing on innovations, performance evaluations, and case studies. This will help identify knowledge gaps, best practices, and technologies that can be adapted or improved.

- Needs Assessment

Engage with stakeholders, including municipal authorities, industrial operators, environmental scientists, and community representatives, to assess the specific needs and challenges related to wastewater treatment in various contexts. This assessment will guide the development of tailored solutions.

- Technology Selection and Design

Based on the literature review and needs assessment, select a range of promising eco-friendly treatment technologies (e.g., membrane bioreactors, constructed wetlands, anaerobic digestion) for further development. Design integrated treatment systems that combine multiple technologies to enhance efficiency and sustainability.

- Pilot Testing and Optimization

Develop and implement pilot-scale studies of the selected treatment systems to evaluate their performance under real-world conditions. Monitor key performance indicators, such as pollutant removal rates, energy consumption, and resource recovery efficiency. Use the data collected to optimize system design and operation.

- Economic and Feasibility Analysis

Conduct a comprehensive economic analysis to assess the cost-effectiveness of the proposed technologies, including initial investment, operational costs, and potential savings from resource recovery. Evaluate the feasibility of implementation in different contexts, considering factors such as local regulations and available infrastructure.

- Environmental Impact Assessment

Perform an environmental impact assessment to evaluate the potential benefits and drawbacks of the proposed technologies. This assessment should include life cycle analysis to quantify the overall environmental footprint of the treatment systems.

- Stakeholder Engagement and Feedback

Facilitate workshops and discussions with stakeholders to gather feedback on the proposed technologies and their applicability. Incorporate this feedback into the design process to ensure that the solutions meet community and industry needs.

- Documentation and Reporting

Compile the findings, methodologies, and recommendations into a comprehensive report that outlines the conceptualized eco-friendly wastewater treatment technologies. Highlight key insights, best practices, and policy recommendations for implementation.

- Dissemination and Collaboration

Share the results through presentations, publications, and partnerships with relevant organizations and institutions. Foster collaboration among stakeholders to encourage the adoption of the proposed technologies and promote knowledge sharing.

- Monitoring and Continuous Improvement

Establish a framework for ongoing monitoring and evaluation of implemented technologies to assess their long-term performance and adaptability. Use this information to drive continuous improvement and innovation in eco-friendly wastewater treatment solutions.

By following this methodology, the research aims to develop advanced, sustainable wastewater treatment technologies that are effective, economically viable, and adaptable to a range of industrial and municipal applications.

2.1 Implementation Strategies

The implementation strategy for eco-friendly wastewater treatment technologies involves a structured approach to ensure successful deployment and integration of these solutions in both industrial and municipal settings. The strategy encompasses the following key components:

2.1.1 Stakeholder Engagement and Collaboration

Establish partnerships with key stakeholders, including government agencies, municipal authorities, industrial operators, environmental organizations, and community groups. Facilitate workshops and meetings to foster collaboration, gather input, and build consensus on the proposed technologies.

2.1.2 Pilot Projects

Initiate pilot projects to test the developed eco-friendly wastewater treatment technologies in real-world settings. Select diverse locations that represent different wastewater characteristics and treatment challenges to evaluate performance and adaptability. Use pilot studies to demonstrate the feasibility and benefits of the technologies.

2.1.3 Regulatory Compliance and Permitting

Work closely with regulatory agencies to ensure that the proposed technologies meet existing standards and requirements. Develop a clear understanding of permitting processes and engage with stakeholders to navigate regulatory hurdles effectively.

2.1.4 Capacity Building and Training

Provide training programs for operators, engineers, and municipal staff to enhance their knowledge and skills in managing and maintaining eco-friendly wastewater treatment systems. Capacity building is essential for ensuring the successful operation of new technologies.

2.1.5 Funding and Financial Support

Identify potential funding sources, such as government grants, public-private partnerships, and environmental impact investment funds, to support the implementation of eco-friendly technologies. Develop financial models that demonstrate the long-term economic benefits of resource recovery and operational efficiency.

2.1.6 Monitoring and Evaluation Framework

Establish a robust monitoring and evaluation framework to assess the performance of implemented technologies. Define key performance indicators (KPIs) related to pollutant removal, energy consumption, resource recovery, and overall system efficiency. Regularly analyze data to identify areas for improvement.

2.1.7 Public Awareness and Education Campaigns

Launch public awareness campaigns to educate communities about the benefits of eco-friendly wastewater treatment technologies. Highlight the environmental and economic advantages of sustainable practices to garner public support and acceptance.

2.1.8 Integration with Existing Infrastructure

Develop strategies for integrating eco-friendly technologies into existing wastewater treatment infrastructure. Assess current systems to identify opportunities for retrofitting or upgrading to incorporate new technologies effectively.

2.1.9 Sustainability Assessment

Conduct periodic sustainability assessments to evaluate the long-term impacts of implemented technologies on water quality, energy use, and resource recovery. Use findings to refine strategies and promote continuous improvement.

2.1.10 Feedback Loop and Adaptation

Create a feedback mechanism to gather insights from operators, stakeholders, and the community. Use this feedback to adapt and refine technologies, training programs, and operational practices to better meet the evolving needs of wastewater treatment.

By implementing this strategy, the goal is to ensure the successful deployment of eco-friendly wastewater treatment technologies that enhance sustainability, improve water quality, and contribute to the circular economy in both industrial and municipal applications.

2.2 Proposed Model

The proposed model for eco-friendly wastewater treatment technologies integrates innovative processes and sustainable practices tailored for both industrial and municipal applications. This holistic approach aims to enhance efficiency, promote resource recovery, and minimize environmental impact. This model combines multiple treatment processes to maximize pollutant removal and resource recovery. It begins with pre-treatment, involving initial screening and sedimentation to remove large solids and debris, reducing the load on subsequent treatment stages. Biological treatment utilizes advanced processes such as membrane bioreactors (MBRs) and moving bed biofilm reactors (MBBRs) to degrade organic matter and nutrients, while chemical treatment incorporates advanced oxidation processes (AOPs) for removing emerging contaminants that traditional methods may not effectively address. The model also emphasizes resource recovery through technologies for nutrient extraction, such as struvite precipitation, and energy generation via biogas production from anaerobic digestion.

Additionally, the model promotes the integration of renewable energy sources to power treatment processes, thereby reducing reliance on fossil fuels and lowering greenhouse gas emissions. Solar power systems can supply energy, particularly in areas with abundant sunlight, while capturing and using biogas produced during anaerobic digestion can contribute to the energy needs of the facility. For areas with limited infrastructure or where centralized systems are impractical, decentralized treatment options are promoted. Constructed wetlands can utilize natural processes for effective wastewater treatment, suitable for both urban and rural settings. The development of modular treatment units allows for easy deployment and scalability based on specific community needs and wastewater characteristics. Implementing smart technology and data analytics optimizes operations and improves decision-making. Real-time monitoring of key performance indicators (KPIs) such as water quality, energy consumption, and operational efficiency can be achieved using IoT devices, while predictive analytics can utilize machine learning algorithms to forecast system performance and maintenance needs, allowing for proactive management and reducing downtime.

Engaging local communities fosters awareness and support for eco-friendly practices. Involving community members in planning and decision-making ensures proposed solutions align with local needs and preferences. Educational programs can develop outreach initiatives to inform stakeholders about the benefits of eco-friendly wastewater treatment technologies and the importance of sustainable water management. Finally, establishing a supportive regulatory and policy framework facilitates the adoption of eco-friendly technologies. Proposing financial incentives, grants, and subsidies encourages municipalities and industries to invest in sustainable solutions. Collaborating with regulatory bodies can help develop clear guidelines and standards for the implementation and monitoring of these technologies.

This proposed model for eco-friendly wastewater treatment technologies aims to create a sustainable, efficient, and resilient approach to wastewater management. By integrating advanced treatment processes, renewable energy sources, decentralized solutions, and community engagement, the model seeks to enhance water quality, promote resource recovery, and contribute to environmental sustainability in both industrial and municipal contexts.

2.2.1 The Model

The model for eco-friendly wastewater treatment technologies conceptualizes advanced, sustainable designs tailored for both industrial and municipal applications. This model is built on the principles of efficiency, resource recovery, and environmental stewardship, integrating various treatment processes to optimize wastewater management. At the core of the model is an integrated treatment system that combines multiple processes for comprehensive pollutant removal. This includes pre-treatment methods such as screening and sedimentation to eliminate large solids, followed by biological treatment using advanced technologies like membrane bioreactors (MBRs) and moving bed biofilm reactors (MBBRs). These processes effectively degrade organic matter and nutrients, while advanced oxidation processes (AOPs) are employed to target emerging contaminants that conventional methods may overlook.

The model emphasizes resource recovery as a central objective. Through innovative techniques, such as struvite precipitation, valuable nutrients are extracted from wastewater. Additionally, anaerobic digestion is utilized to generate biogas, which can be converted into renewable energy, thus supporting the energy needs of the treatment facility. Renewable energy integration is another key feature of the model. By incorporating solar power systems and harnessing biogas, the treatment processes can operate with reduced dependence on fossil fuels, leading to lower greenhouse gas emissions. This not only enhances the sustainability of the treatment facilities but also contributes to energy resilience. For areas with limited infrastructure, the model promotes decentralized treatment solutions. Constructed wetlands are highlighted as effective systems that utilize natural processes to treat wastewater, making them suitable for both urban and rural environments. Additionally, modular treatment units can be developed for easy deployment and scalability, accommodating specific local needs and wastewater characteristics.

Data-driven management plays a crucial role in optimizing the performance of eco-friendly wastewater treatment technologies. Real-time monitoring of key performance indicators (KPIs), such as water quality and energy consumption, is facilitated through IoT devices. Predictive analytics, powered by machine learning algorithms, allows for proactive maintenance and management, ensuring operational efficiency and reliability. Community engagement is fundamental to the success of the model. By involving local stakeholders in the planning and decision-making processes, the solutions developed can align closely with community needs and preferences. Educational programs aimed at raising awareness about the benefits of eco-friendly wastewater treatment can foster public support and understanding.

The model also addresses the need for a supportive regulatory and policy framework. By proposing financial incentives, grants, and subsidies, it encourages the adoption of eco-friendly technologies among municipalities and industries. Collaboration with regulatory bodies is essential to establish clear guidelines and standards that facilitate implementation and monitoring. In summary, this model for eco-friendly wastewater treatment technologies is designed to create a sustainable and resilient approach to wastewater management. By integrating advanced treatment processes, renewable energy sources, decentralized solutions, and community engagement, the model seeks to enhance water quality, promote resource recovery, and contribute to environmental sustainability in both industrial and municipal contexts.

2.2.2 Benefits and Implications

The implementation of eco-friendly wastewater treatment technologies offers numerous benefits and implications for both industrial and municipal applications. These advantages extend beyond immediate environmental improvements, impacting economic, social, and regulatory dimensions as well. The primary benefit of eco-friendly wastewater treatment technologies is the significant reduction in environmental pollution. By effectively removing pollutants, including nutrients and emerging contaminants, these technologies help protect water bodies and ecosystems, leading to improved water quality and biodiversity. This contributes to the preservation of natural resources, which is essential for sustaining life and supporting various ecological functions. Another critical advantage is resource recovery. Eco-friendly systems can extract valuable nutrients, such as nitrogen and phosphorus, from wastewater, transforming waste into resources. This nutrient recovery not only reduces the need for synthetic fertilizers, promoting sustainable agriculture, but also minimizes the environmental impact associated with fertilizer production and use. Furthermore, biogas generated from anaerobic digestion can be utilized as a renewable energy source, contributing to energy independence and reducing greenhouse gas emissions.

Economic implications are also significant. By adopting advanced treatment technologies, municipalities and industries can achieve cost savings in the long run. Enhanced efficiency and reduced operational costs can lead to lower energy consumption and maintenance expenses. Additionally, the recovery of resources can create new revenue streams, further bolstering economic sustainability. Socially, eco-friendly wastewater treatment technologies can improve public health and quality of life. By minimizing the discharge of harmful pollutants into the environment, these systems help reduce health risks associated with contaminated water. Improved water quality can enhance recreational opportunities and boost local economies reliant on clean water resources. The implementation of eco-friendly technologies also aligns with global sustainability goals and regulatory frameworks. As governments increasingly prioritize environmental protection and sustainability, adopting these advanced treatment solutions can help organizations meet regulatory requirements and enhance their compliance with environmental standards. This proactive approach can improve the reputation of municipalities and industries, positioning them as leaders in sustainable practices.

Moreover, eco-friendly wastewater treatment technologies can foster community engagement and awareness. Involving local stakeholders in the planning and implementation process promotes a sense of ownership and responsibility for water management. Educational initiatives can raise public awareness about the importance of sustainable wastewater practices, encouraging responsible behaviors and further supporting environmental stewardship. Lastly, these technologies promote resilience in wastewater management systems. By integrating renewable energy sources and decentralized treatment options, communities can enhance their capacity to respond to environmental challenges, such as climate change and resource scarcity. This adaptability ensures that wastewater treatment systems remain effective and sustainable in the face of evolving challenges.

In summary, the benefits and implications of eco-friendly wastewater treatment technologies are far-reaching, encompassing environmental protection, resource recovery, economic efficiency, public health, regulatory compliance, community engagement, and resilience. By conceptualizing and implementing these advanced, sustainable designs, both industrial and municipal applications can contribute to a healthier, more sustainable future.

3 Conclusion

In conclusion, the conceptualization of eco-friendly wastewater treatment technologies represents a pivotal advancement in the pursuit of sustainable water management for both industrial and municipal applications. By integrating innovative treatment processes, resource recovery mechanisms, and renewable energy sources, these technologies not only enhance wastewater treatment efficiency but also significantly reduce environmental impacts. The benefits of adopting these advanced designs extend beyond improved water quality; they foster economic sustainability, promote public health, and support compliance with regulatory frameworks. The recovery of valuable resources from wastewater underscores the potential for transforming waste into assets, contributing to a circular economy that prioritizes sustainability.

Moreover, the involvement of local communities in the planning and implementation of eco-friendly systems cultivates awareness and engagement, further reinforcing the importance of responsible water management. As communities and industries navigate the complexities of environmental challenges, these technologies offer a resilient pathway toward achieving sustainability goals. Ultimately, the integration of eco-friendly wastewater treatment technologies holds the promise of creating a healthier environment and enhancing the quality of life for present and future generations. By prioritizing innovation and sustainability in wastewater management, we can contribute to a more sustainable and resilient future for our planet.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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